CENTER FOR
COMPUTER AIDED DESIGN

September 26, 2002

College of Engineering
The University of Iowa
Iowa City, Iowa

FOCUS AREAS OF RESEARCH

DESIGN AND OPTIMIZATION

- **Design Sensitivity Analysis and Optimization**
- **Geometric Modeling and CAD**
- **Multidisciplinary Design Optimization**
- **Optimization Algorithms**
- **Reliability-Based Design Optimization (Design for 6-Sigma)**
- **Topology Optimization**

SOLID MECHANICS

- **Computational Mechanics**
- **Composite Materials**
- **Meshfree Methods**
- **Probabilistic Mechanics & Reliability**
- **Biomechanics**

HUMAN-SYSTEM INTERACTION

- **Human Interaction with Automation**
- **Human Computer Interaction VR**
- **Human Performance**
- **Digital Human Simulation**
- **Ergonomic Design**

KINEMATICS AND DYNAMICS

- **Mechanisms and Robotics**
- **Multibody Dynamics and Simulations**
- **Real Time Dynamics and Haptics**
- **Nonlinear Vibrations**

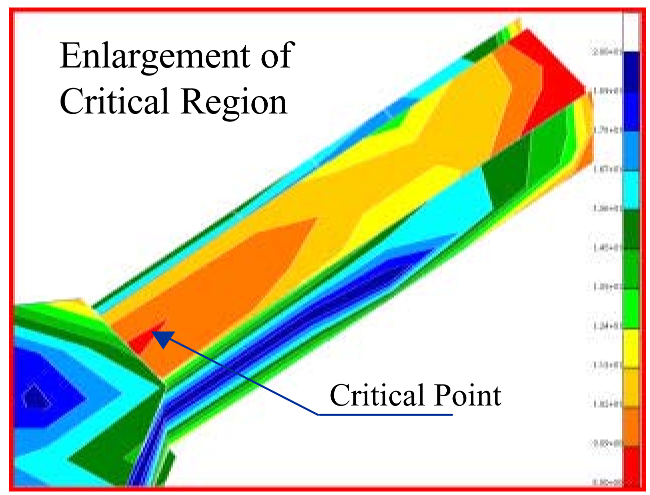
RESEARCH PERSONNEL

- 12 (+4) Faculty Members:
  - Three Civil & Environmental Engineering
  - Three Industrial Engineering
  - Five Mechanical Engineering
  - One Mathematics
  - One Mechanical Systems (Multiphysics or Multiscale) and Three Industrial Engineering (Uncertainty & Reliability) Faculty Are Being Recruited
- 12 Staff Members:
  - 5 Ph.D.s and 1 M.S. - Technical Staff
  - 3 M.S.s, 2 B.S.s, 1 Certified Secretarial - Support Personnel

ARMY MECHANICAL PHYSICS-OF-FAILURE MODELING AND SIMULATION

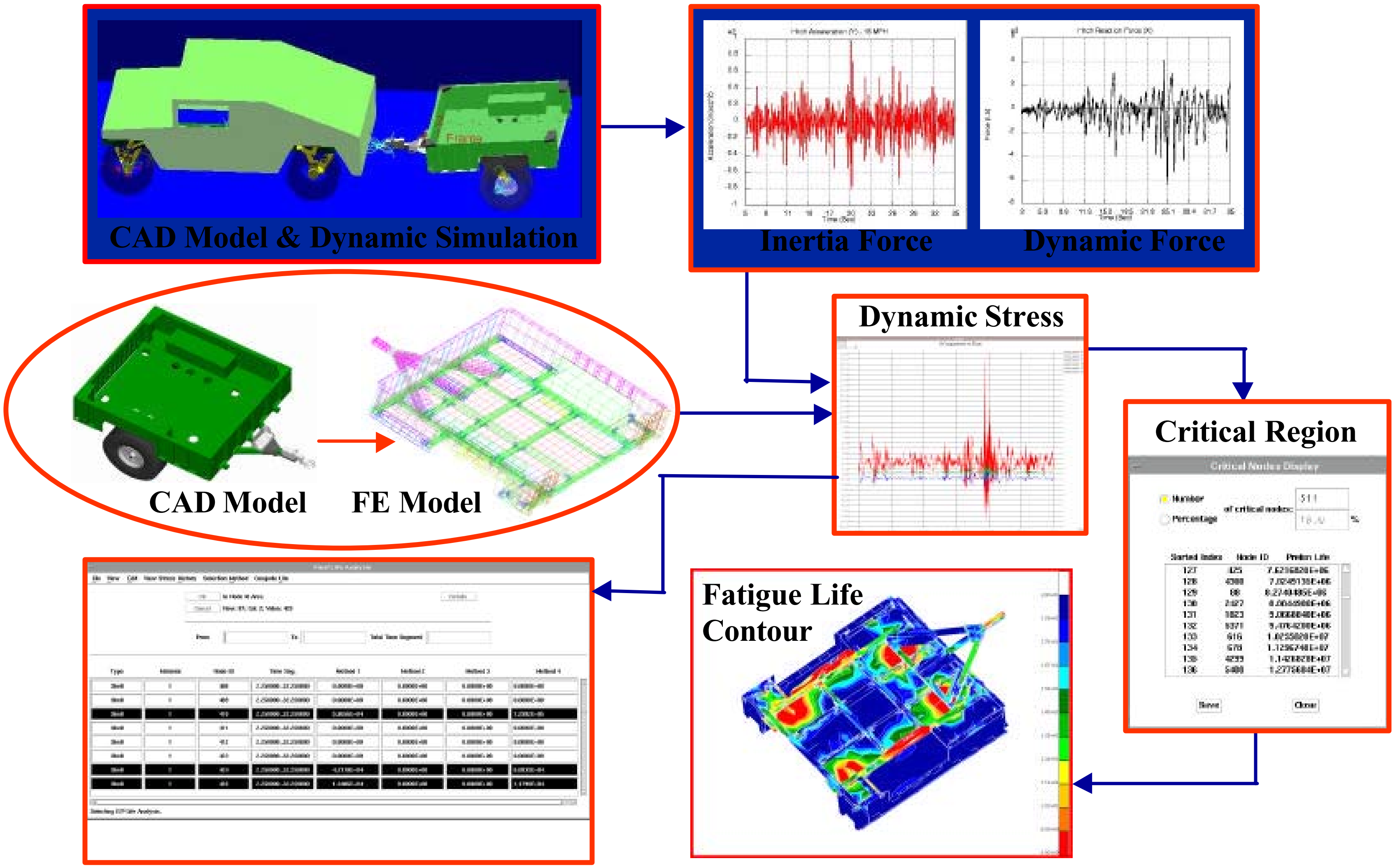
Objectives

- ✓ Validate dynamics loading from system level to component level
- ✓ Use lab/field test data to validate loading & reliability predictions
- ✓ Validate dynamic strain using measured data
- ✓ Predict fatigue life based on measured strain and compare with simulation life
- ✓ Develop repeatable modeling and simulation process and Book of Knowledge



Drawbar cracked after 1,671 miles on Perryman course #3 at averaged speed of 12.5 mph.

ARMY MECHANICAL PHYSICS-OF-FAILURE MODELING AND SIMULATION



The University of Iowa
College of Engineering

Center for Computer-Aided Design

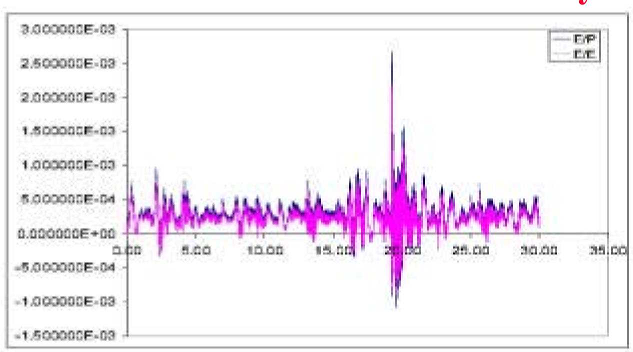
ARMY MECHANICAL PHYSICS-OF-FAILURE MODELING AND SIMULATION

Dynamic Stress & Strain Computation

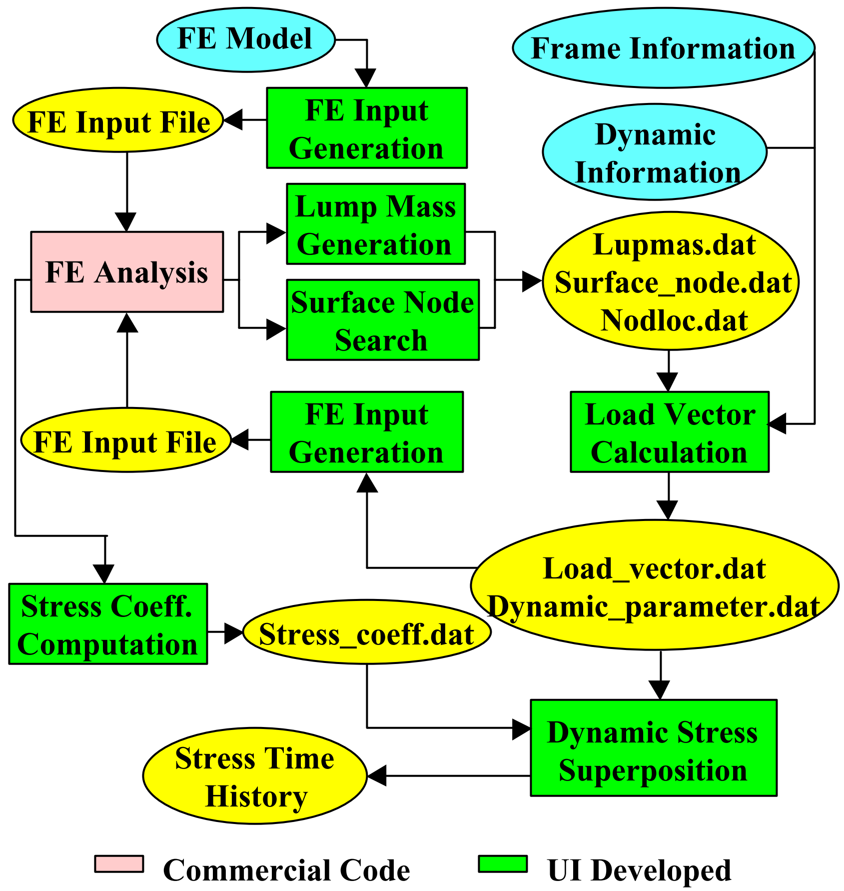
Dynamic Stress Computation

- Extract dynamic analysis results (Duty cycle information)
- Quasi-static load vectors generation
- Stress coefficient calculation
- Dynamic stress superposition
- Calculate von Mises stress and principal stress histories
- Multi-axial elastic-plastic strain conversion using elastic finite element analysis results

Elastic-Plastic Strain Time History

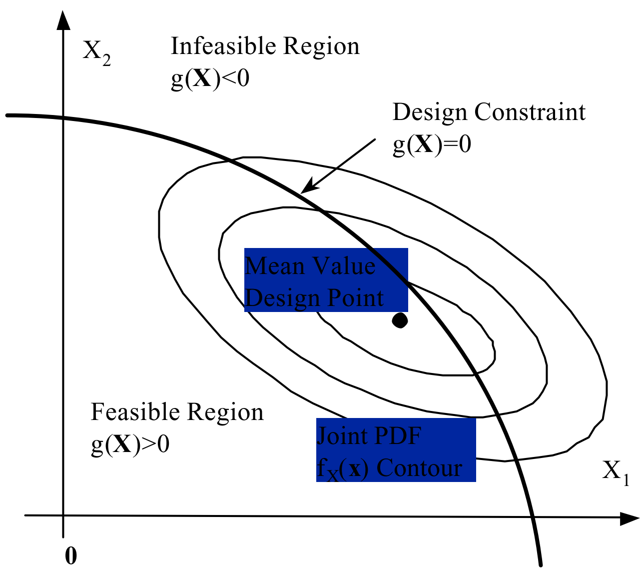


Dynamic Stress Computation Flow Chart

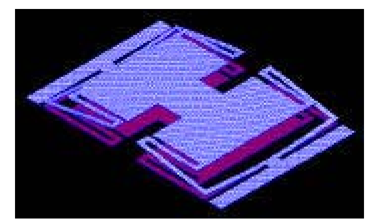


RELIABILITY-BASED DESIGN OPTIMIZATION

- Due to competitive market, designs are pushed to the limit of the design constraints using optimization, leaving little or no room in manufacturing variability ⇒ Leads to higher manufacturing costs, which hinders product marketability.



Automotive



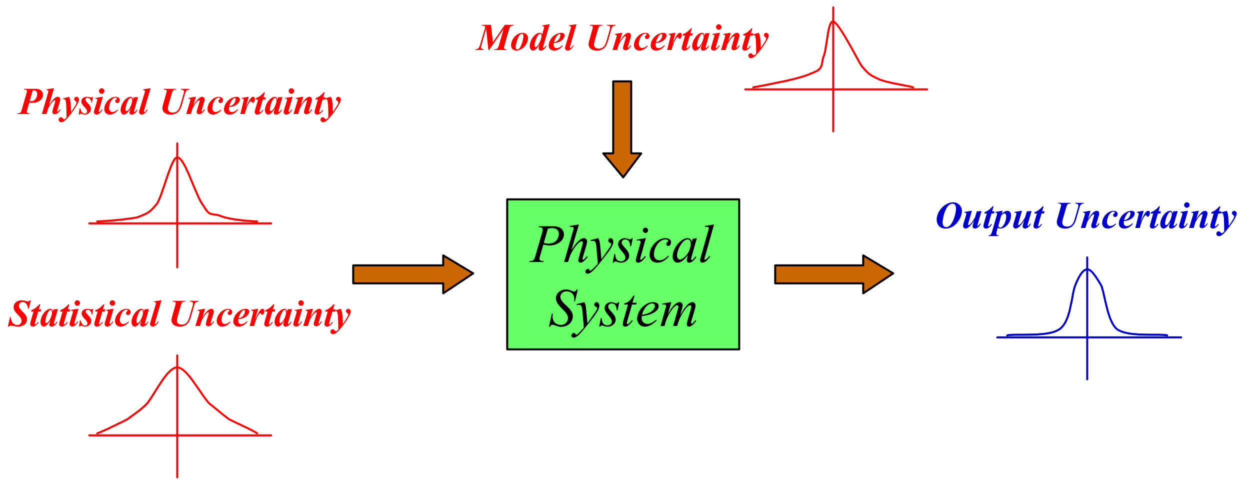
MEMS

Small Scale!

- RBDO methodology provides not only optimum design, but also a confidence range ⇒ 6-Sigma Design for Manufacturing.
- Reliability-Based Design vs. Robust Design

UNCERTAINTY TYPES

- Physical Uncertainty: Material properties, dimensions, & loads
- Statistical Uncertainty: Due to limited sample sizes, probabilistic model (distribution type and its parameters) is uncertain – lack of information
- Model Uncertainty: Uncertainty of mathematical models and numerical methods due to simplifying assumptions, unknown boundary conditions, unknown effects of of other variables not included in the model, etc.



PERFORMANCE MEASURE APPROACH OF RBDO

Probabilistic Constraint $F_{Gi}(0) - \Phi(-\beta_{ti}) \le 0$

$\beta_{ti} = 6 \Rightarrow$ 6-Sigma Design

$\Phi^{-1}(\bullet)$

$\Phi^{-1}(F_{Gi}(0)) + \beta_{ti} = -\beta_{si} + \beta_{ti} \le 0$

β_{si} : Reliability Index

Reliability Index Approach (RIA): Reliability Analysis

$F_{Gi}^{-1}(\bullet)$

$-F_{Gi}^{-1}(\Phi(-\beta_{ti})) = -G_{pi} \le 0$

G_{pi}: Probabilistic Performance Measure

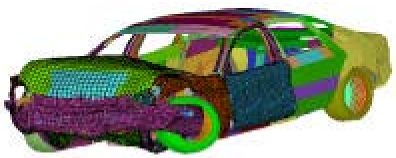
Performance Measure Approach (PMA): Inverse Reliability Analysis

$$\text{RIA: } -\beta_s + \beta_t \equiv \Phi^{-1}\left(\int_{G(\mathbf{X})<0} \cdots \int f_{\mathbf{X}}(\mathbf{x})d\mathbf{x}\right) + \beta_t \le 0$$

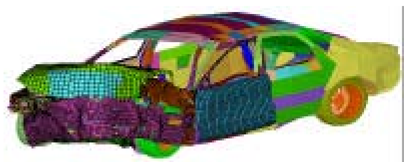
$$\text{PMA: } -G_p \equiv -F_G^{-1}\left(\int_{G(\mathbf{X})<g^*} \cdots \int f_{\mathbf{X}}(\mathbf{x})d\mathbf{x}\right) \le 0$$

$\Rightarrow$ FORM & Hybrid Mean-Value Method

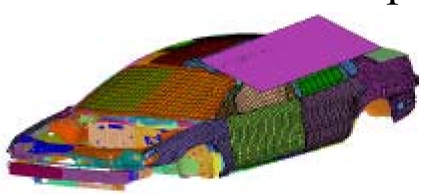
MULTIDISCIPLINARY CRASH RBDO



Frontal Impact



50% Frontal Offset Impact



Roof Crush

Side Impact

Analyses Using
RADIOSS on
SGI Origin 3000

Minimize **Vehicle Weight**

Subject to

<u>Roof Crush Constraints</u>:

$P(\text{Crush distance } D \leq 5'') \geq 90\%$

$P(\text{Critical load peak } P_{cr} \geq 27\text{kN}) \geq 90\%$

<u>Full Frontal Impact Constraints</u>:

$P(\text{HIC} \leq 370) \geq 90\%$

$P(\text{Chest G} \leq 42) \geq 90\%$

$P(P_{total} \leq 10\ \%) \geq 90\ \%$

<u>50% Frontal Offset Impact Constraints</u>:

$P(\text{Toe board intrusion} \leq 11'') > 90\%$

<u>Side Impact Constraints</u>:

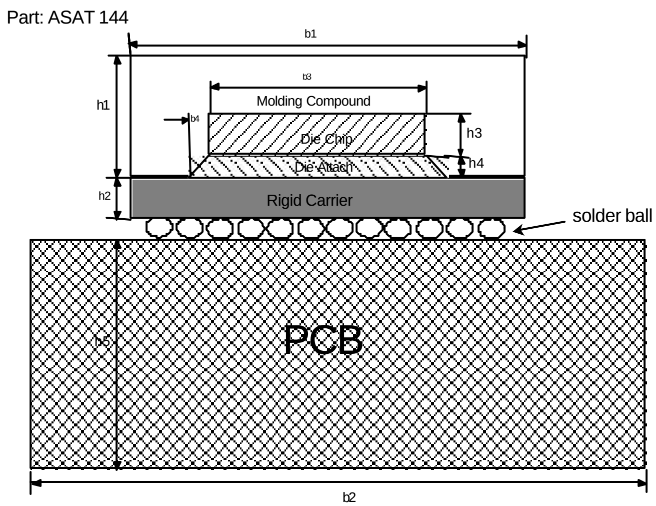
$P(V^*C \leq 0.58) \geq 90\%$

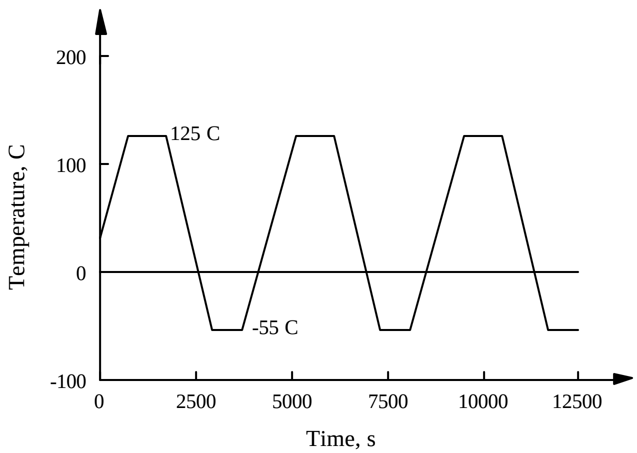
$P(D_{\text{upper rib}} \leq 27.2) \geq 90\%$

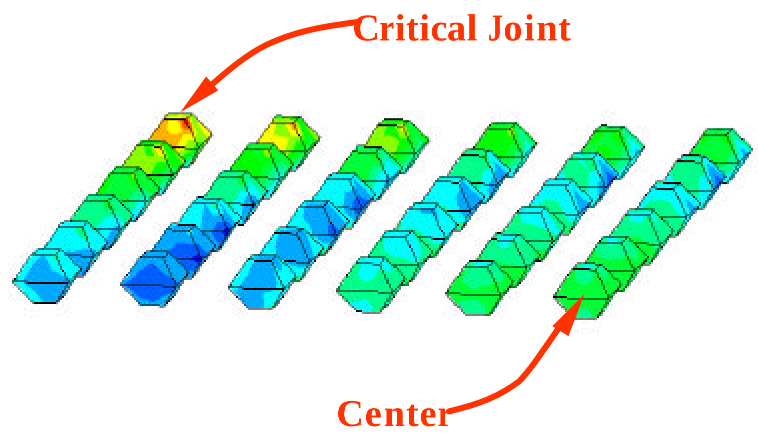
$P(D_{\text{middle rib}} \leq 27.2) \geq 90\%$

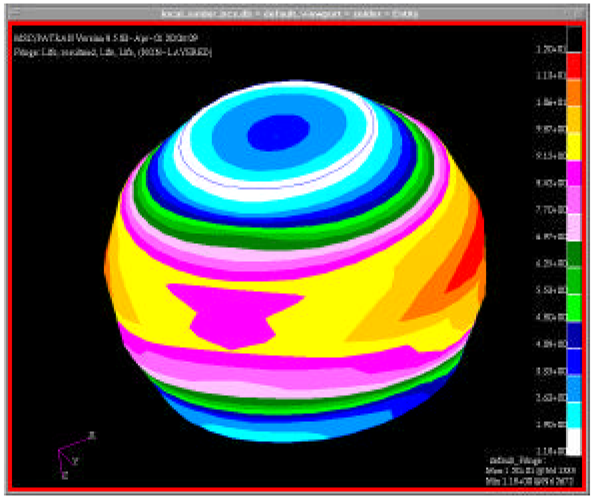
$P(D_{\text{lower rib}} \leq 27.2) \geq 90\%$

MICRO-ELECTRONICS RELIABILITY









Fatigue Life

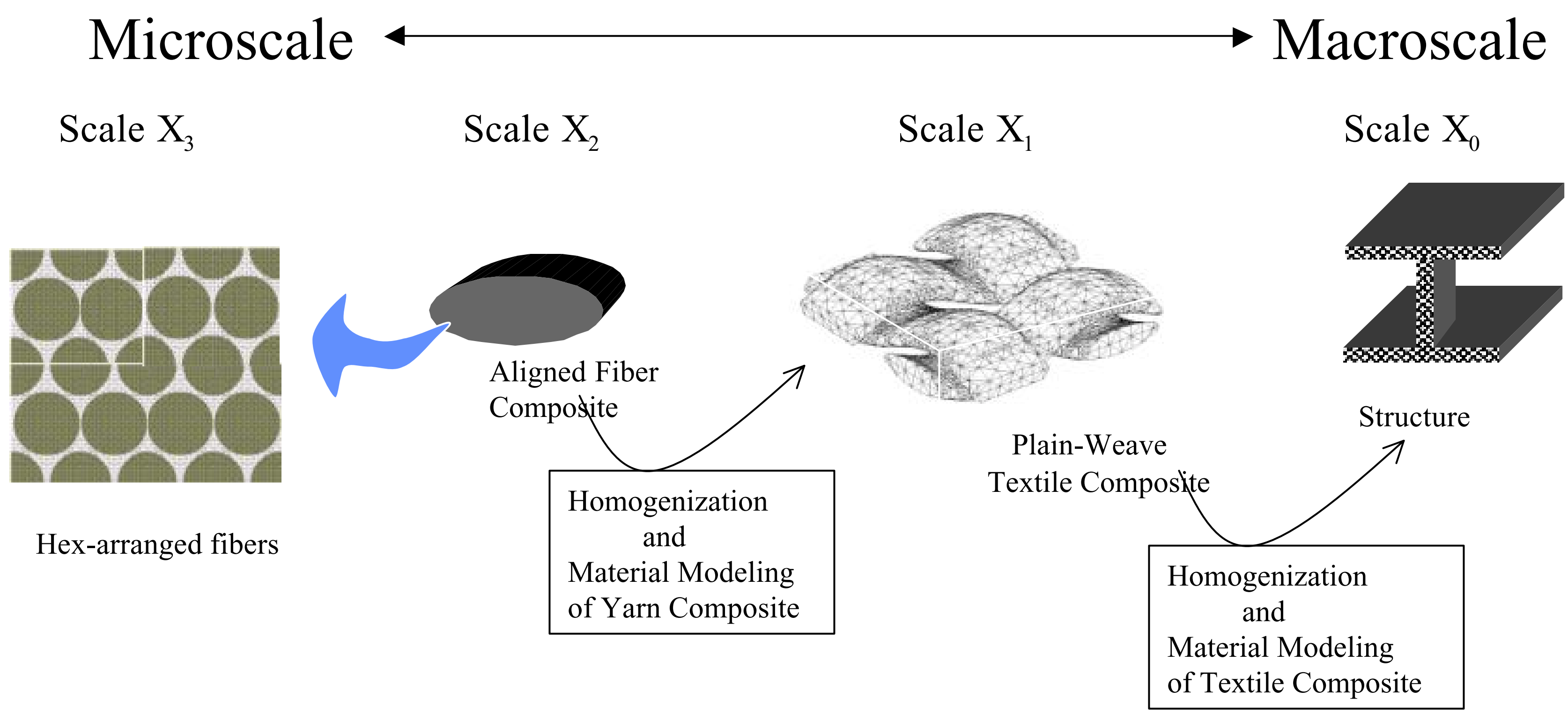
ISSUES IN MULTISCALE MODELING OF HETEROGENEOUS MATERIALS

- Develop and employ micro-scale analysis tools that relate microstructure, and micromechanics.

- Homogenize:
    - Take micro-scale property-structure behaviors and translate (via averaging or filtering) to macroscopic response.

- Localize:
    - Given a state of macroscopic deformation, temperature and the microstructure, use micromechanics to update microfields and microstructure.
- Essence:
    - Determine how microscale phenomena show up on the macroscale;
    - Determine how macroscopic conditions evolve microstructure;

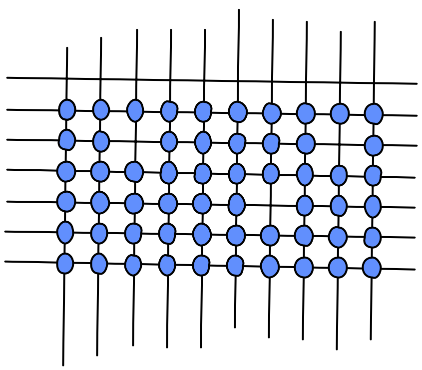
MULTI-SCALE ANALYSIS WITH COMPOSITES



MULTI-SCALE ANALYSIS WITH METALS

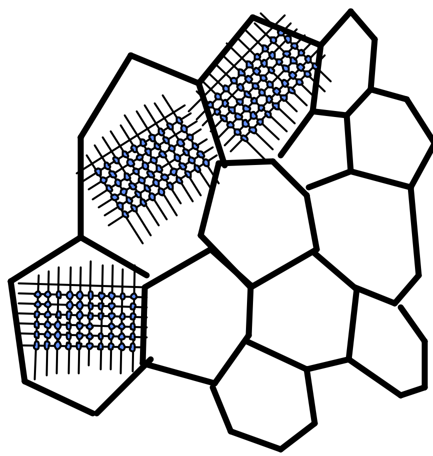
Microscale ⟷ Macroscale

Scale X_3



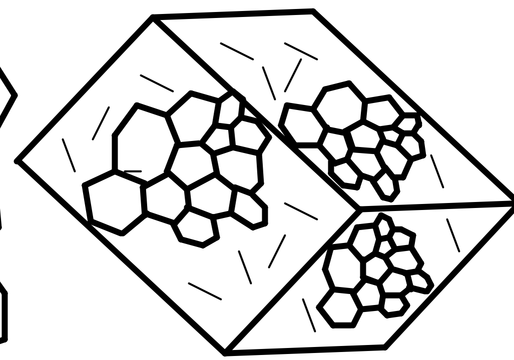
Crystalline lattice with dislocations

Scale X_2



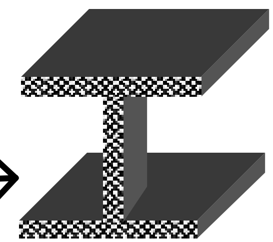
Individual grain scale (with dislocations)

Scale X_1



Continuum scale. (Many grains with microcracks)

Scale X_0



Structural Element Scale

SCALE-BRIDGING RELATIONS

$$\boldsymbol{X}^{n+1} = \boldsymbol{X}^{n} / \varepsilon_{n+1}$$

$$\boldsymbol{x}^2 - \boldsymbol{X}^2 = \boldsymbol{u}^2(\boldsymbol{X}^0, \boldsymbol{X}^1, \mathbf{X}^2) = \boldsymbol{u}^1(\boldsymbol{X}^0, \boldsymbol{X}^1) + \boldsymbol{u}^{2*}(\boldsymbol{X}^2) \qquad \text{microscale}$$

$$\boldsymbol{x}^1 - \boldsymbol{X}^1 = \boldsymbol{u}^1(\boldsymbol{X}^0, \boldsymbol{X}^1) = \boldsymbol{u}^0(\boldsymbol{X}^0) + \boldsymbol{u}^{1*}(\boldsymbol{X}^1) \qquad \text{mesoscale}$$

$$\boldsymbol{x}^0 - \boldsymbol{X}^0 = \boldsymbol{u}^0(\boldsymbol{X}^0) \qquad \text{macroscale}$$

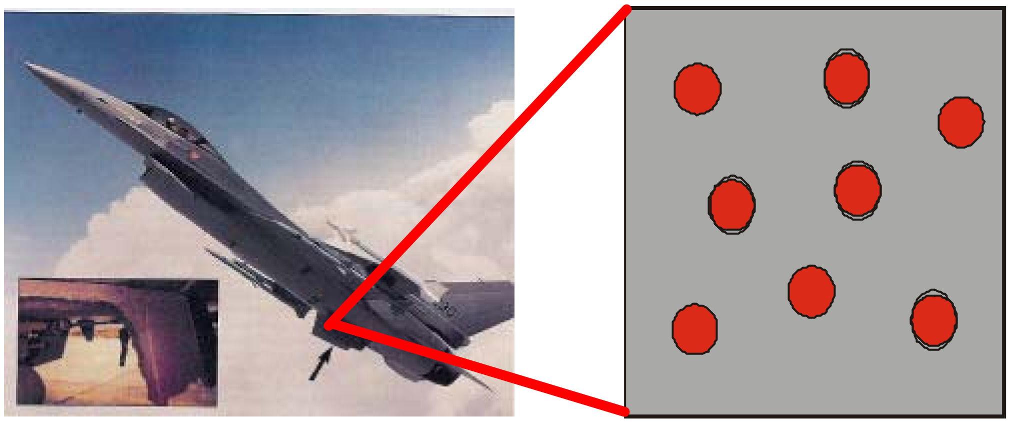
$$\boldsymbol{u}^{n+1} = \boldsymbol{u}^{n} + \varepsilon_{n+1}\boldsymbol{u}^{n+1*} + \cdots$$

$$\boldsymbol{s}^{n} = \left\langle \boldsymbol{s}^{n+1}\left(\boldsymbol{X}^0, \cdots, \boldsymbol{X}^{n+1}\right)\right\rangle_{\mathrm{O}_\mathrm{s}^{\mathrm{X}^{n+1}}}; \ \boldsymbol{F}^{n} = \left\langle \boldsymbol{F}^{n+1}\left(\boldsymbol{X}^0, \cdots, \boldsymbol{X}^{n+1}\right)\right\rangle_{\mathrm{O}_\mathrm{s}^{\mathrm{X}^{n+1}}}$$

$$\boldsymbol{s}^{n+1} = \boldsymbol{s}^{n}(\boldsymbol{X}^0, \cdots, \boldsymbol{X}^{n}) + \boldsymbol{s}^{n+1*}(\boldsymbol{X}^{n+1}); \quad \boldsymbol{F}^{n+1} = \boldsymbol{F}^{n}(\boldsymbol{X}^0, \cdots, \boldsymbol{X}^{n}) + \boldsymbol{F}^{n+1*}(\boldsymbol{X}^{n+1})$$

$$\left\langle \boldsymbol{s}^{n+1*}\right\rangle_{\mathrm{O}_\mathrm{s}^{\mathrm{X}^{n+1}}} = \boldsymbol{0}; \ \left\langle \boldsymbol{F}^{n+1*}\right\rangle_{\mathrm{O}_\mathrm{s}^{\mathrm{X}^{n+1}}} = \boldsymbol{0}.$$

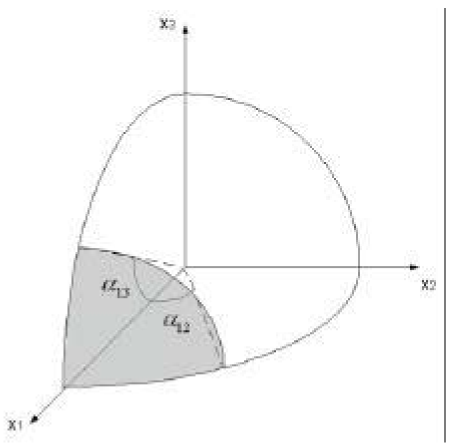
MICROMECHANICS-BASED DAMAGE MODEL FOR COMPOSITES



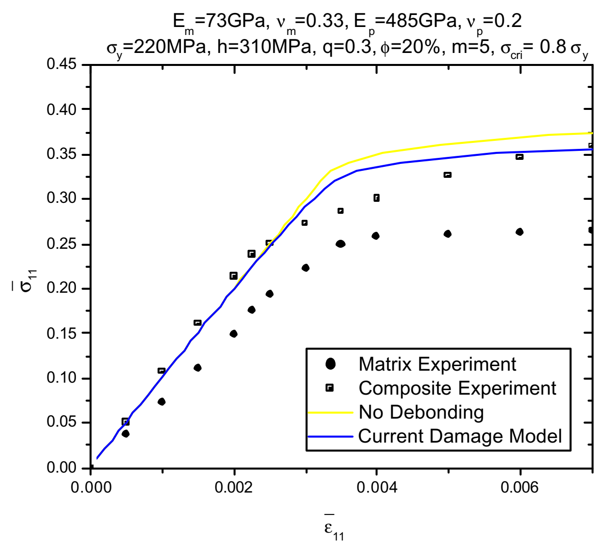
F-16 Ventral Fins SiCp/Al

Debonding SiCp/Al

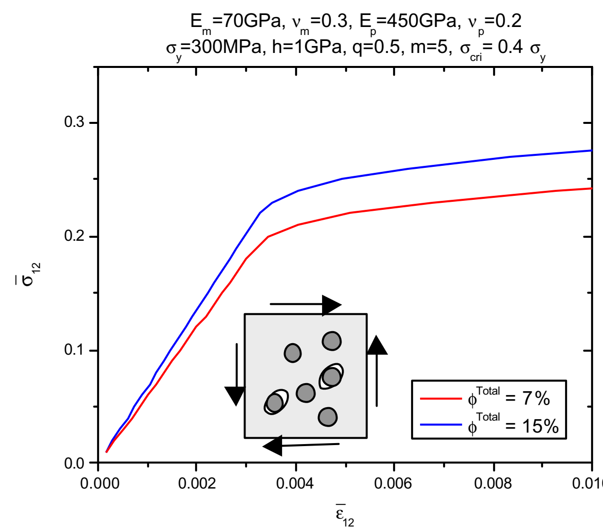
Prognosis of Elastoplastic-Damage Behavior of SiCp/Al Composites (L. Sun 2002)



Debonding Modes



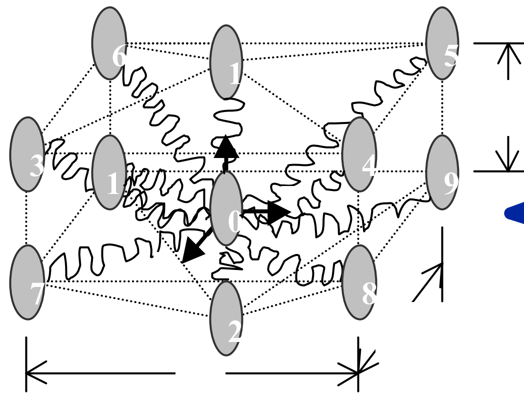
Uniaxial Tension



Shear Loading

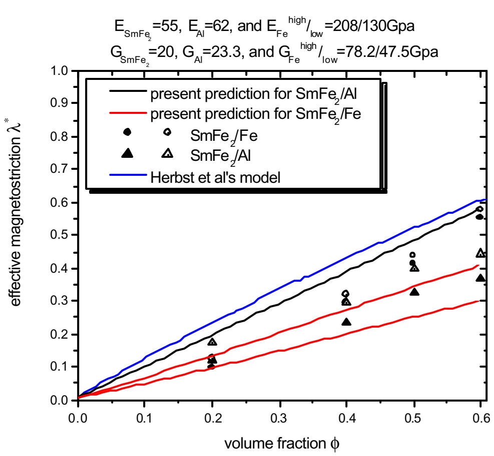
MICROMECHANICS-BASED HYPERELASTIC MODEL FOR MAGNETOSTRICTIVE COMPOSITES

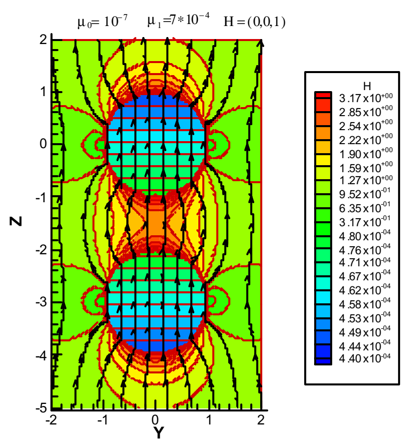
Ferromagnetic Particle-Reinforced Composites (Jolly 1996)



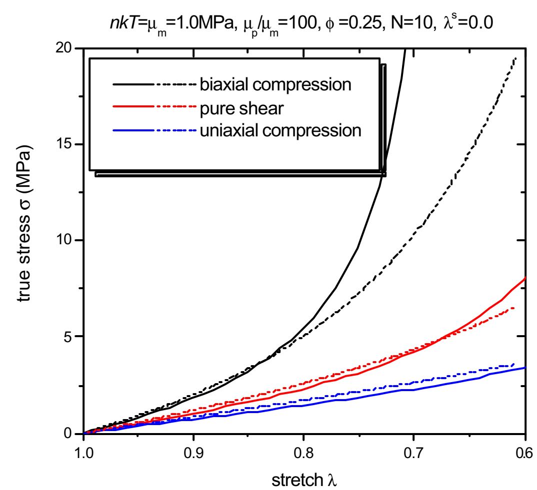
Micromechanical Modeling of Magnetostrictive Composites

Quantitative Prediction of Finite Elasticity of Fe Particle Intelligent Composites (L. Sun 2002)





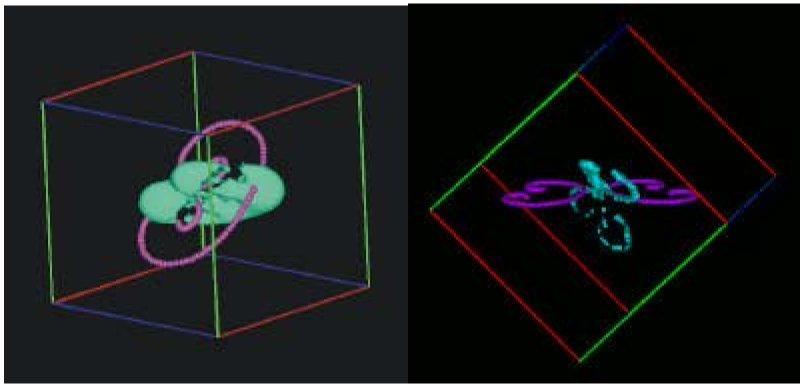
Magnetic Field of Fe-Reinforced Composites



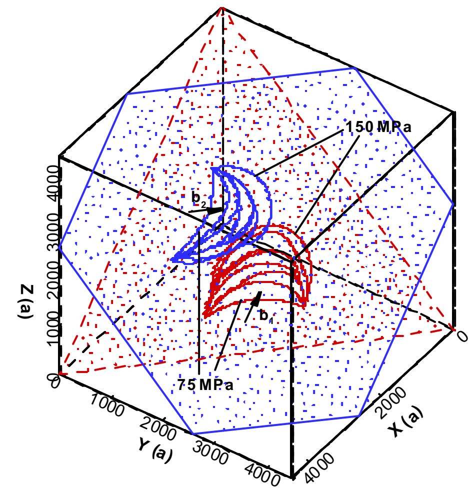
The University of Iowa
College of Engineering

Center for Computer-Aided Design

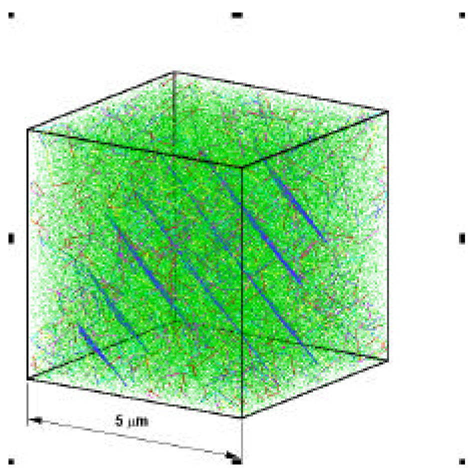
MICROPLASTICITY OF MATERIALS
3-D DISLOCATION DYNAMICS SIMULATION



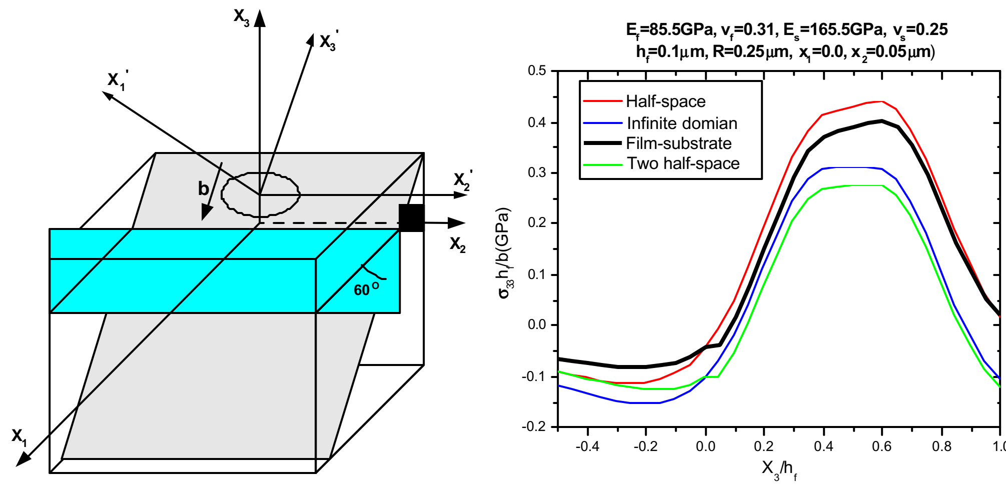
Stress Simulation of Frank-Read Source Dislocations (L. Sun 1999)



Plastic Slip Emanating from Two F-R Sources Interacting with Point Defects in Cu. (L. Sun 2000)



Simulation of Plastic Channel Generation due to Dislocation Interaction with Point Defects (L. Sun 2001)

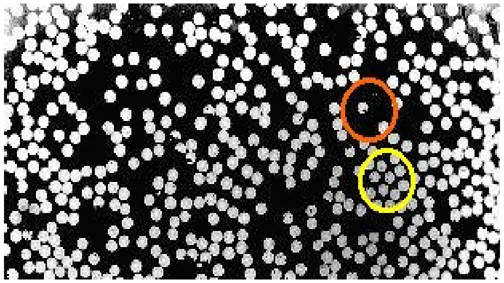


Stress Simulation of Thin Film Dislocation Loops (L. Sun 2002)

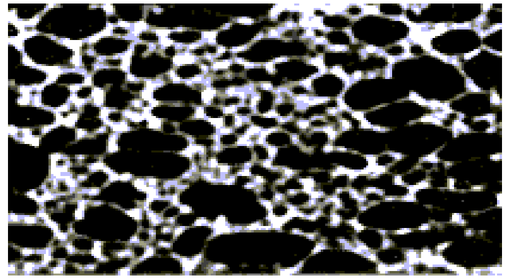
The University of Iowa
College of Engineering

Center for Computer-Aided Design

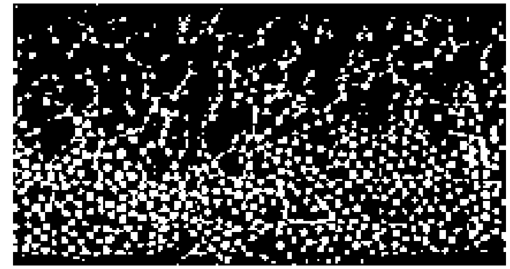
STOCHASTIC MATERIAL MODEL



Graphite fiber
in epoxy matrix



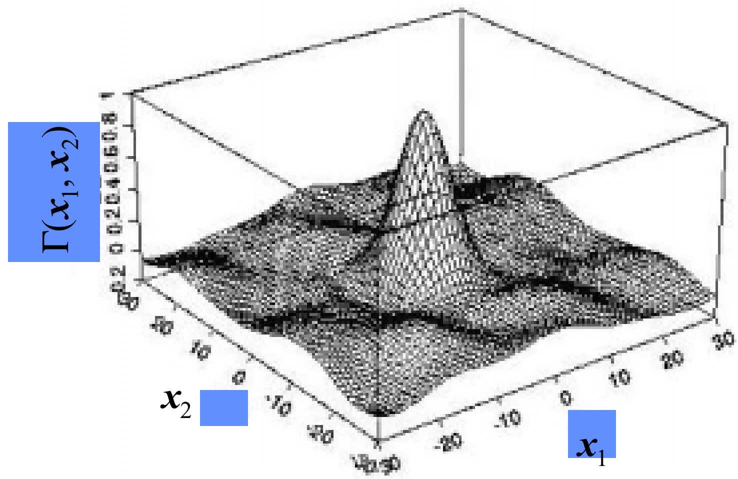
Cellular Aluminum



Functionally Graded
Material

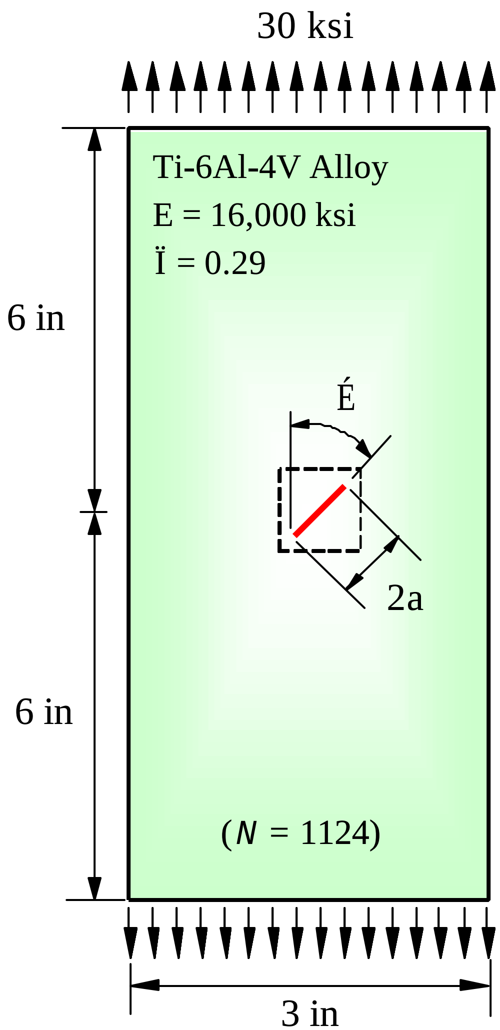
Histogram of
material property
field

PDF at any given point

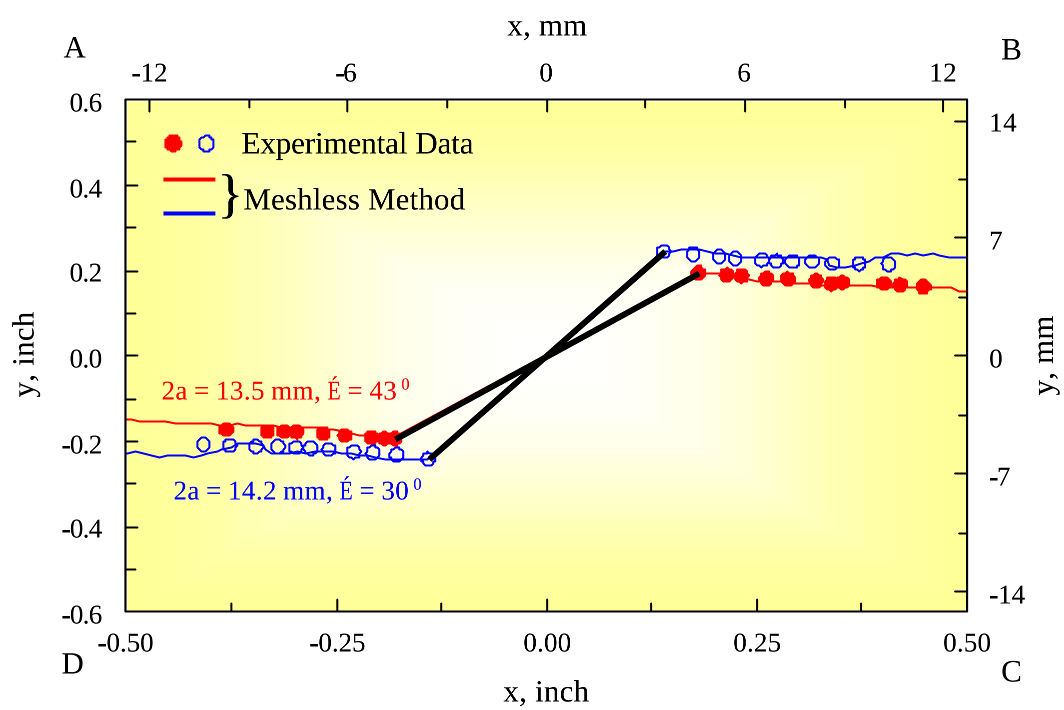


Correlation between any two points

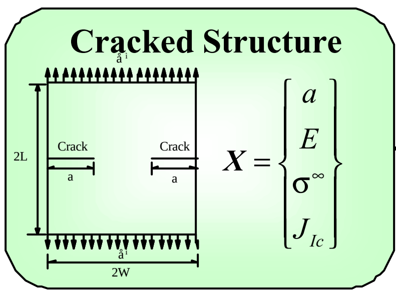
FRACTURE & DAMAGE SIMULATION

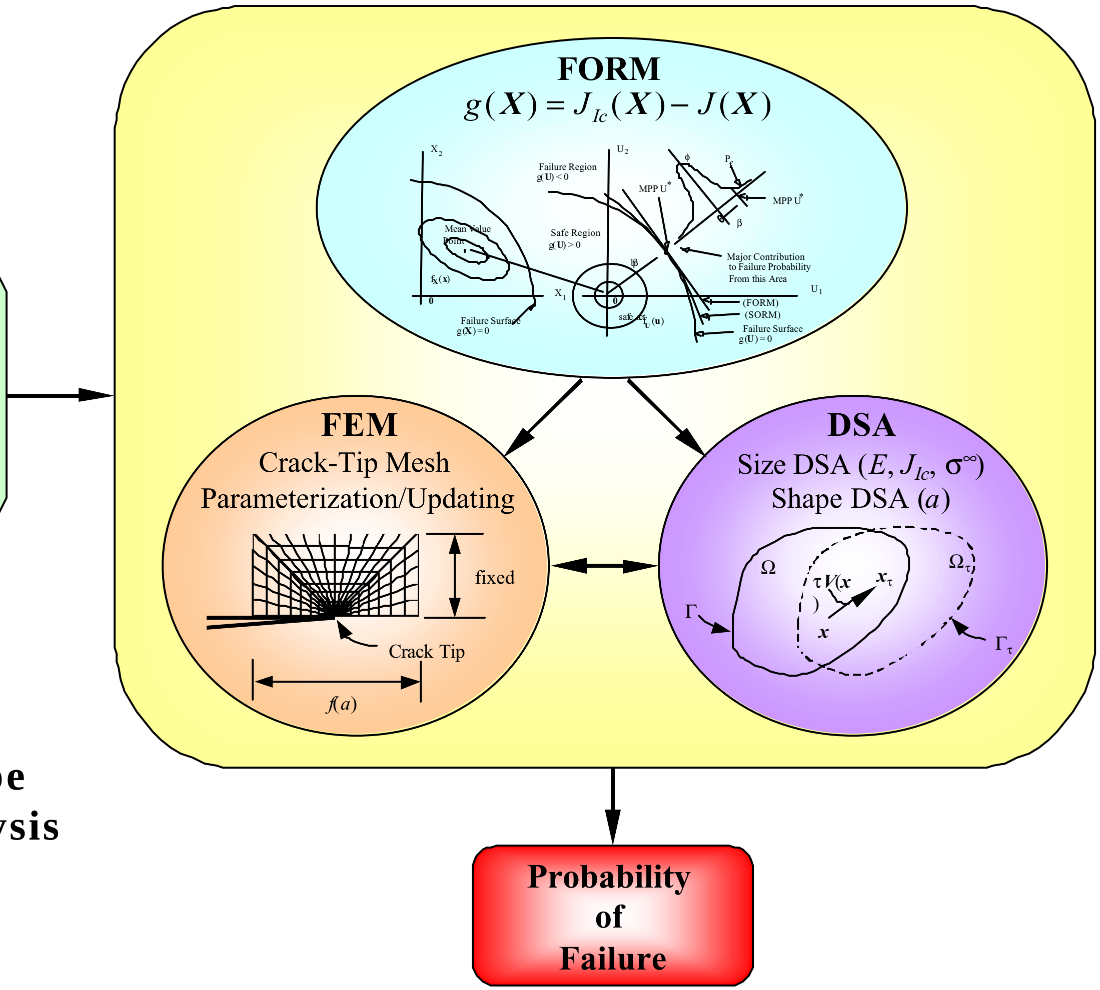


- **FEM Continuum Damage Mechanics**
- **Mesh-Free Simulation of Fracture**



STOCHASTIC FRACTURE MECHANICS

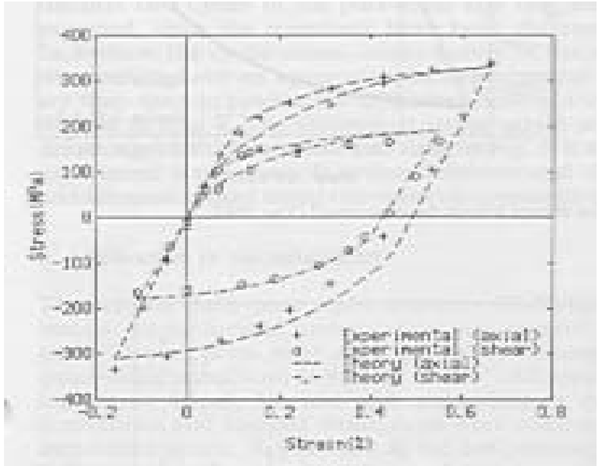




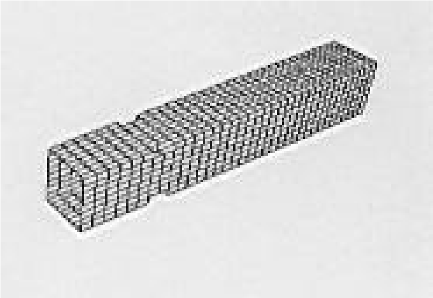
- **Continuum Shape Sensitivity Analysis**
- **Probabilistic Fracture and Reliability**

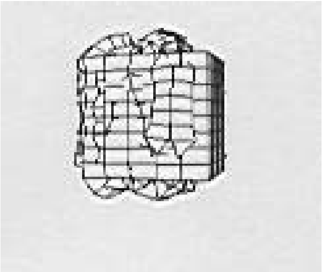
INVERSE PROBLEMS IN MECHANICS USING OPTIMIZATION

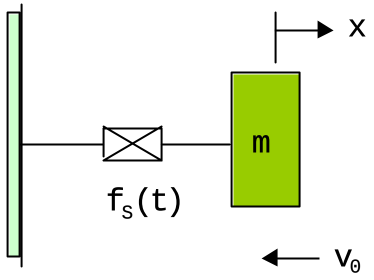
- Identification of materials (constitutive models)
  - ✓ *Constitutive models for elastoplastic and viscoplastic material behavior*



- ✓ *Development of simplified models for impact loading*
- ✓ *Development of simplified models for crushing of structural components*


Finite Element Model of a Tube

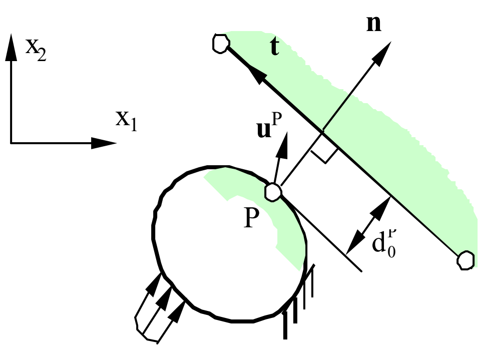

Crushed Tube due to Impact



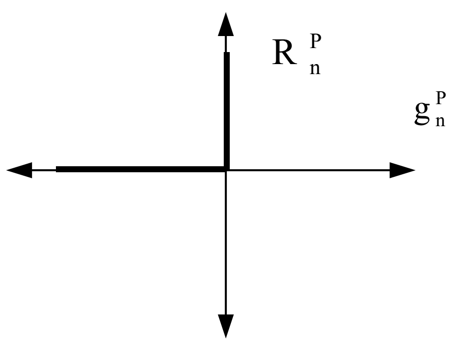
Simplified Single DOF Model

FRICTIONAL CONTACT ANALYSIS USING OPTIMIZATION

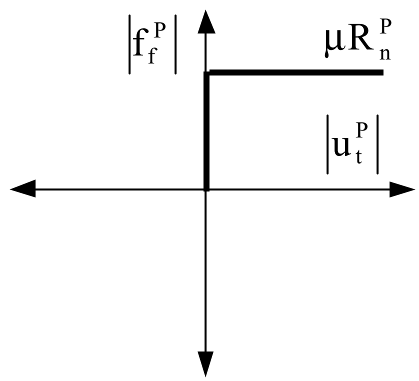
- Solution with the current frictional contact analysis methods depends on the time/load step and value of the penalty parameter
- New methods developed using Augmented Lagrangian approach
  - ✓ *Finite value of the penalty parameter is calculated automatically*
  - ✓ *Accuracy of the solution is not dependent on the time/load step or the starting value of the penalty parameter*



Contact Configuration

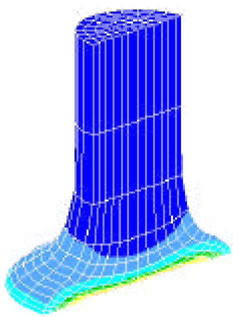


Unilateral Contact



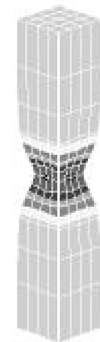
Coulomb's Friction

CONTINUUM MECHANICS CONSTITUTIVE MODELING & SIMULATIONS

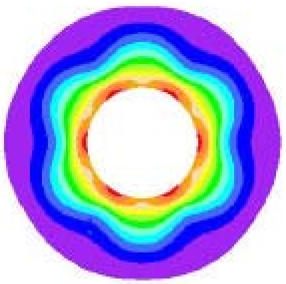


Impact

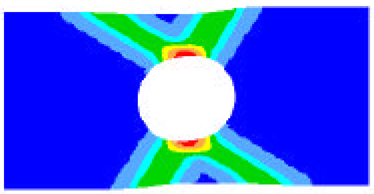
- **Modeling of Structured Media**
  - Theory for evolving microstructure
  - Anisotropic solids
- **Large-Strain Constitutive Modeling and Computation**
  - Computational plasticity
  - Large strain thermoelasticity
- **Treatment for Material Constraints**
  - Incompressibility
  - Wrinkling



Necking



Fibrous Membrane



Shear Band in Anisotropic solids